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# MOCA: Multi-Objective Cell Association for Device-to-Device Communications

Christoforos Vlachos, *Student Member, IEEE*, Vasilis Friderikos *Member, IEEE*

**Abstract**—It is widely accepted that Device-to-Device (D2D) communication is envisaged to become the key enabler of direct localized communication between mobile nodes in future wireless networks. However, little attention has been paid on an important aspect that can potentially affect both the performance of D2D and cellular transmissions, that of the D2D cell association. In this paper, a multi-objective cell association (*MOCA*) optimization framework for orchestrating a large number of D2D links in a multi-cell network is introduced. To this end, and without loss of generality, a differentiated Fractional Frequency Reuse (FFR) scheme is considered as the interference-limiting method, especially for cell-edge users, and we assume the provision of different resource pools for D2D and cellular users which can vary according to their location. Under this assumption, we develop a set of integer linear programming (ILP) optimization formulations for D2D links, part of which fall within the coverage area of different neighbouring base stations (BSs). The main purpose is to achieve improved network traffic balancing via an efficient cell association scheme. Furthermore, we provide an iterative Randomized Resource Allocation algorithm (*i-RRA*), that roots its logic on the differentiated FFR model in order to increase overall network throughput. Wide set of numerical investigations demonstrate the benefits offered by *MOCA* as well as the throughput gains that can be achieved through *i-RRA* compared to existing solutions.

**Index Terms**—Device-to-Device (D2D) communications, cell association, optimization, resource allocation, fractional frequency reuse (FFR).

## I. INTRODUCTION

Current 3GPP LTE-A systems, commercially introduced as 4G, include a number of technological components that support heterogeneity and improve the network's performance as well as the overall user experience. However, with the advent of 5G technology and the expected traffic growth [1], further enhancements need to be taken into consideration to render future networks a trustworthy solution that will meet the booming user demands. Among those, a newly integrated technological paradigm is that of the Device-to-Device (D2D) communication to account not only for public safety and commercial use, but also enhanced quality of service (QoS) and perceived user experience for proximate based connections [2]. One of its main benefits is its offloading attribute that can alleviate part of the traffic developed to a BS by reusing the cellular spectrum [3]. Especially for popular events (e.g. release of software updates or viral videos), the D2D technology can not only provide network offloading but can be deemed as a spectrum efficient solutions for emerging 5G systems.

In cellular networks, the ongoing densification, combined with the irregularity of the cells' shape and the co-existence of multiple user types, can lead to different levels of load congestion in the cell areas (from lightly loaded to severely congested cases). Such congestion episodes need to be effectively managed in order to increase network capacity [4]. To this end, intelligent cell association (CAS) and traffic balancing techniques shall be applied to address the resource and capacity limitations, which can lead to network bottleneck creation. The principal aim of this paper is to provide a multi-objective cell association optimization framework for D2D communications, named *MOCA*, and pave the way for a low complexity, iterative randomized resource allocation algorithm to increase network throughput.

### A. Device-to-Device (D2D) communications

Localized communications are proven to not only offer high data rates but also spectral and energy efficiency if effectively exploited through the network. In these terms, D2D communication paradigm is expected to alleviate part of the BSs' traffic load by leveraging the ability of two close-ranged devices to communicate directly without the need for the data to be routed via the BS. Its benefits arise mainly from the proximity gain that it offers as well as from the reuse gain that the underlay property can provide [5][6]. The primary aims of introducing such a technique is to: (i) enable opportunities for new proximity services, (ii) provide novel means to alleviate traffic congestion episodes, (iii) achieve higher data rates, low latency as well as controllable transmit power and (iv) enhance network capacity by exploiting the merits that localized, short-range wireless peer-to-peer communications can offer [7].

In this work, the focus is turned on the inband underlay property of D2D communications where the paired users can reuse the available cellular (licensed) spectrum. In that case, D2D links that underlay a cellular infrastructure will be mainly controlled by the network to ensure higher spectrum controllability [8]. In terms of network operation, D2D communications provide some new challenges due to their dynamic nature and the new intra/inter cell interference patterns that will generate. The coexistence of conventional cellular links and D2D pairs perplexes the problem of resource allocation due to the limited physical resources. Each BS can serve only a limited number of connections simultaneously, and for this reason, the overall traffic load should be efficiently balanced among the serving BSs. Therefore, it is important to apply efficient D2D-based cell association techniques in order to not only provide satisfactory QoS for all user equipments (UEs), but also enhance the spectral efficiency and system's capacity to accommodate more users to serve.

C. Vlachos and V. Friderikos are with the Centre for Telecommunications Research (CTR), Department of Informatics, at King's College London (KCL), London, UK. e-mail: {christoforos.vlachos, vasilis.friderikos}@kcl.ac.uk.

Due to the ongoing proliferation of social networking based applications, the chance for two users in close proximity to share data between each other might significantly increase in the future, leading to the irregular emergence of multiple D2D pairs in future networks. Hence, the orchestration of a large number of D2D links in the network still remains a challenging task. In the following subsection, we provide a statistical based characterization to examine the possible emergence of D2D links where part of the cell-edge ones might cross different cell coverage areas. The reason for examining the latter is the ambiguity of a crossing link to be associated only with one of the candidate serving BSs. Like in conventional cellular communications, several aspects might influence the cell-edge D2D links performance and its association with a specific BS. These are, for example, the link range, path loss characterization and the distance from each BS.

### B. Statistical bound for macro-cell crossing D2D links

We consider a highly dense scenario where multiple D2D links are uniformly distributed in a seven-hexagonal cell scenario (the establishment procedure of D2Ds is out of the scope of this paper, however a summary of the proximity-based session initiation ([9]) and link formation steps can be found in [10][11]). Part of them will be consisting of links where the involved D2D UEs (DUEs) will fall within the geographical area of different BSs (red links shown in Fig. 1). As we are now witnessing further cell densification and overall decrease of the cell size in order to increase spatial capacity of future networks, the case of two nodes being located in different cells might become a notable proportion of the D2D communication links.

We correlate the problem of having cell-crossing D2D links with the Buffon's Needle (BN) problem [12]. This problem examines the probability that a needle lies in a position where it intersects one of the parallel lines when dropped on a ruled two-dimensional space. In our case, this probability could refer to a D2D communication link where each one of the DUEs geographically belongs to different cell. Below, we provide an estimation of the lower bound regarding the number of D2D pairs that is not straightforward which BS will undertake their control. In a heterogeneous network setting, this number can be distinctly higher due to the existence of small cells within the serving area of macro BSs.

Let us assume hexagonal cells with dimension  $h = 2d$  (Fig. 1) and define with  $l_{n_1, n_2}$  the distance between two DUEs  $n_1$  and  $n_2$ , it is proven that the probability  $p_0$  that both UEs are located in the same cell is approximated as follows [12]:

$$p_0 = 1 - \frac{1}{3} \left( \frac{l_{n_1, n_2}}{h} \right)^2 - \frac{l_{n_1, n_2}}{h} \left( 4 - \sqrt{3} \frac{l_{n_1, n_2}}{h} \right) \frac{1}{\pi}. \quad (1)$$

Consequently, the crossing probability for D2D links is the complement of (1):

$$p = 1 - p_0 = \frac{1}{3} \left( \frac{l_{n_1, n_2}}{h} \right)^2 + \frac{l_{n_1, n_2}}{h} \left( 4 - \sqrt{3} \frac{l_{n_1, n_2}}{h} \right) \frac{1}{\pi}. \quad (2)$$

In the case of a highly congested network, this probability could provide a statistical approximation of the ratio of crossing D2D links in relation to the total number of D2D pairs

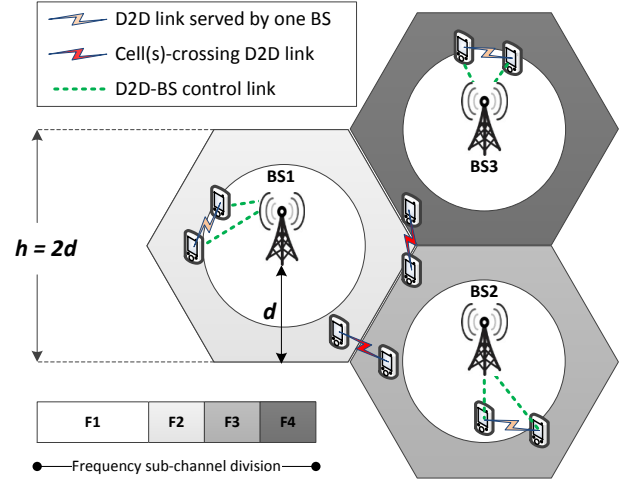


Fig. 1. D2D communication links in a multi-cell environment (with  $h = 2d$ ). A number of links might cross the boundaries between neighbouring cells, hence link nodes could be conventionally connected to different BSs.

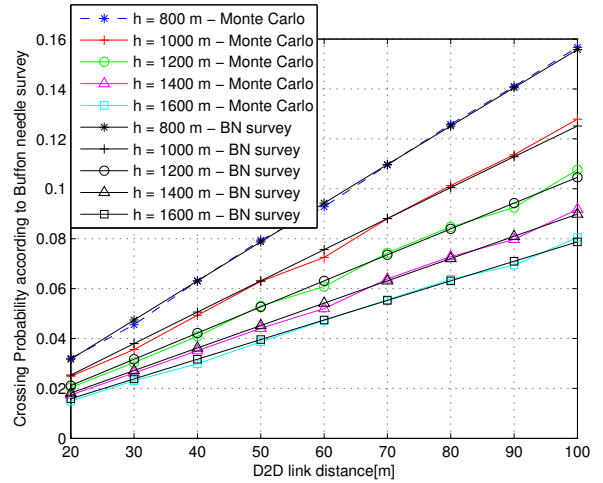


Fig. 2. Buffon's Needle survey and Monte Carlo simulations comparison. This figure signifies the probability of having a D2D link crossing the boundaries of neighbouring cells. Convergence is achieved for a high number of iterations.

in the macro-cell based network. By running extensive Monte Carlo simulations (1000 iterations), Fig. 2 shows that, when uniformly distributing a fixed, designated number of links of varying link ranges and for different cell dimensions, this ratio becomes almost tangent to the BN probability estimations. As expected, the link crossing probability increases in proportion with the range of the D2D communication link.

However, the above analysis corresponds to an ideal scenario where cells form hexagonal shapes of the same size and are served by center-located BSs. To reflect a more realistic deployment scenario, BSs can be distributed according to a Poisson Point Process (PPP) in space, and each one of them controls a Voronoi region (cell) with a random area [13]. Because of the irregularity of the cell shapes as well as the PPP distribution of the BSs, the terms inner (interior)

and outer (cell-edge) user do not have the same geometrical interpretation as in hexagonal layouts. Hence, in order for a BS to characterize a user as an interior or a cell-edge one, a pre-specified SINR threshold is defined and compared with a user's average SINR; when it is below this threshold, it is labeled as a cell-edge UE, otherwise as interior.

### C. Related work

Cell association in cellular networks has been a critical challenge for network operators due to the ongoing increase of user demands in an underlying resource-limited infrastructure. The scope of optimizing cell association is to enhance network capacity and accommodate more users simultaneously with respect to their QoS requirements. Although it is a well-investigated area of research, cell association considering the integration of D2D communications as an underlay in cellular networks is a rather unexplored and is the main difference of our work hereafter compared to the existing ones.

Different approaches for cell association in homogeneous and heterogeneous networks (HetNets) exist within the literature. An exemplary work that considers both cases is [14]. It proposes a hybrid base station - mobile station (BS-MS) association policy based on the highest signal-to-interference ratio (SIR) where each MS should be located within a predefined maximum distance from the BS to serve it. The integration of the maximum distance limitation accounts for avoiding frequent handovers. They also study the same problem when distance is set to infinite, and thus highest SIR is the association criterion for single-tier (homogeneous) networks. Also, they further apply the same approach for HetNets and prove its applicability for user offloading to lightly loaded cells. However, no attention has been paid on how the association of communicating D2D users should be realized.

Traditionally in HetNets, cell association has been mainly based on the downlink received signal strength (RSS) estimations of the cellular users. The integration of different access technologies such as pico/femtocells that operate over the same spectrum as that of the underlaid cellular network introduces another degree of complexity due to the developed inter-cell interference. A number of solutions to encounter this problem have been applied, including, inter alia, cell splitting, range expansion, semi-static resource negotiation on third-party backhaul connections, and fast dynamic interference management. Those schemes and their respective benefits are well presented in [15]. However, because of the transmit power disparities of different tiers (macro-cells and small-cells), imbalanced association cases will be appearing as most of the users will be coupled with the macro BS [16]. For this reason, several works leveraged the concept of cell biasing, where the power signal that a UE receives from a deployed small cell is increased by adding a biasing factor [17]. With this method, cell association imbalances can be reduced. Its basic benefit is that network capacity improvement is achieved via its macro-to-small cell offloading attribute [18]. However, this benefit is followed by an associated drawback, especially in highly dense scenarios; this bias-centric user association might lead to unexpected interference patterns as the biased

users will receive interference from the nearby macro-cell [19]. Also, a comprehensive SINR analysis aiming at estimating a user's outage probability as well as the spectral efficiency based on flexible cell association with different BS types (e.g. macro or picocell BSs) is studied in [20]. Therein, a set of numerical results has proven that there might be some cases where the random addition of pico and femtocells to a cellular network will not necessarily increase the network capacity and overall welfare. Extensively, an analytical taxonomy of cell association techniques is detailed in [21].

Considering the aforementioned issues, [22] studied the effect of decoupling downlink (DL) and uplink (UL) sessions in dense HetNets and illustrated the substantial performance gains in the UL for real world scenarios. Not only UL throughput could be significantly improved, but also outage rates are decreased while ensuring a minimum throughput requirement. UL/DL decoupling also provides a cell association-based insight of how future 5G systems could be implemented to ensure valid performance for both sessions [23]. Thus, the UL based CAS should be carefully designed and updated as new technological components such as D2D communications are expected to become a significant proportion of overall connections in cellular networks.

Even though the integration of D2Ds in cellular networks brings up a number of challenges and merits, cell association for this communication paradigm has been barely studied. In [24], the authors proposed an efficient four-step load balancing mechanism when service-requesting users are associated with fully congested cells. The aim there is to transfer part of the developed traffic to the less congested cells in a multi-tier network by making use of relay-enabled direct (D2D) communication. Traffic imbalance phenomena have to be taken into account as, in many cases, the need for direct communication emerges in a rather irregular fashion in space. Further, one of the first works that explicitly considered D2D-centric cell association is [25] which also constitutes the basis of our paper and optimizes cell association with respect to a number of different objectives. Among all, one of the proposed objectives (eq. (9) in [25]) tries to minimize the network load imbalance (different traffic load per BS) with respect to a number of resource related and D2D link association constraints. Last, in [26], the authors developed a joint framework that considers the user association and transmission mode switching between direct and D2D relay modes in order to improve spectral as well as energy efficiency through a closed-form solution. Now, an important question that arises is whether the users that form a D2D pair will be jointly associated with a single BS or with two separate. In the former, the signaling burden is alleviated because both nodes that constitute a D2D pair are associated to the same BS, whereas in the latter extra BS signaling exchange is needed and communication latency increases. A comparison of these cases is the aim of [27] that considers however the overlay concept of D2D communications (orthogonal but licensed spectrum for cellular and D2D UEs). In our work we only consider the case where both users of a D2D link will be coupled with the same BS in the underlay case [28], according to a set of criteria that will be mentioned in the sequel.

Finally, relevant literature that considers explicitly the exis-



tence of cell-crossing D2D links is limited. Significant works that take into account inter-cell D2D links are [29] and [30], both elaborating on the issue of radio resource allocation. The former focuses on optimizing the achievable aggregate network throughput in a three-cell scenario where the D2D users are eligible to reuse the downlink cellular resources. The latter proposes a game-theoretical model where the BSs are competing resources for serving the D2D-related demands, and proceeds by devising a resource allocation algorithm based on Nash equilibrium derivations. In other significant works, cell-crossing links' emergence is also implied as inter-cell D2D UEs, eligible to connect, might be scattered via Poisson Point Process (PPP) modeling in two different cells [31][32].

#### D. Contribution and structure

The key aim is to provide novel cell association optimization solutions for varying network congestion episodes that will boost network capacity to accommodate increased number of users simultaneously. The different proposed solutions belong to an overarching optimization framework which can be deemed as a toolkit for a network operator to optimize network performance based on different selected criteria. The underlay concept of D2D communications (that entails the most spectrum-efficient property among all), combined with an effective balancing of the D2D links along the network, can lead to valuable resource savings. Also, resource allocation for D2D communications needs to be designed in a way that network throughput is boosted. To this direction, and due to the NP-hardness of the joint cell association and resource allocation, the problem is tackled by decoupling it into two sub-problems: first, the cell association problem that can be solved via integer linear programming (ILP) tools and, second, the resource allocation which can be efficiently addressed by an inherently randomized RA algorithm with low computational complexity. In that case, the output solution of the selected cell association optimization problem will become the input for the RA technique that will be provided. Thus, a linear time resource allocation algorithm on top of an optimized CAS configuration is introduced to offer substantial network throughput performance other than resource efficiency.

This paper is an extension of the authors' work in [25]. To the best of our knowledge, this was the first work on cell association optimization that explicitly considers the integration of D2D communication paradigm in cellular networks. Compared to it, in this work we (i) extend the previous optimization problems to include the distributed D2D links in a multi-cell topology and consider different objective functions with respect to interference as well as capacity constraints, and (ii) introduce the aforementioned randomized RA algorithm that bases its resource assignment logic on a differentiated Fractional Frequency Reuse (FFR) scheme and compare its sum-rate performance to existing literature works. The paper is structured as follows: Section II presents the system model and the basis for the realization of cell association for D2D users. Then, Section III provides a multi-objective optimization framework that aims to orchestrate the D2D-caused traffic load with respect to the resource availability and interference-

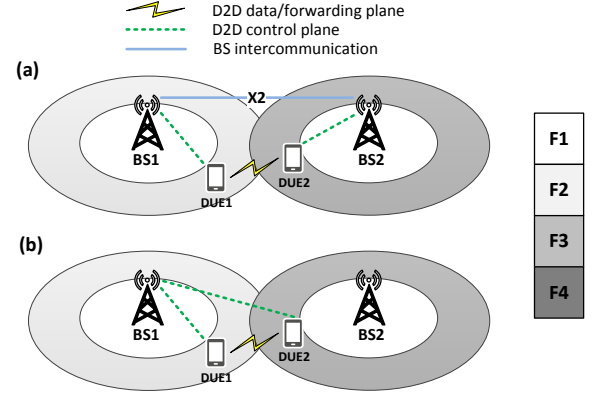


Fig. 3. Signalling exchange for the control of a D2D pair must be reduced: (a) Disjoint DUE association, (b) Joint DUE association.

aware constraints. The resource allocation technique is proposed in Section IV. In Section V, numerical results highlight the performance of this two-stage methodology. Finally, we conclude with remarks and future insights in Section VI.

## II. SYSTEM MODEL

### A. Signaling overhead

The investigated D2D communication links can be categorized into two groups: inner and outer links. The first one includes those D2D links that their paired nodes are both located in a single cell, far from its edges, and are being controlled by the same BS. The second group corresponds to those links that are located in the edge of a cell and their nodes might belong to two different serving geographical areas, as mentioned before. Considering the latter, we presume that the two DUEs could be associated with different BSs. However, this will eventually increase latency and signaling overhead due to the need of the two involved BSs to coordinate the communication (Fig. 3a). Thus, in order to limit these impeding factors, we assume that the overall signaling overhead for this case study can be reduced by providing explicit association of each pair to a single BS, aiming to avoid any BS intercommunication to exchange information (Fig. 3b). **How to properly select a specific BS for associating with a D2D pair will be explained in the sequel.** This approach corresponds to a more realistic and trustworthy networking system as it is easier to be implemented compared to multi-BS association of the connected users. Also, in this way, potential asynchronous communication between the two BSs and control inefficiency can be avoided [28]. Let us now consider that the number of cell-edge D2D pairs is *at least*  $N_{cross}$ . This signaling reduction implies pairwise association with a single BS for each formed D2D pair and, therefore, a signaling exchange saving of  $\frac{N_{cross}}{2}$  cooperative flows among BSs can be achieved.

In this work, we assume that the cell association problem that jointly couples both DUEs of each D2D pair with the same cell/BS can be solved by a centralized controller with knowledge of users' location coordinates. By doing so, we

alleviate BS intercommunication overhead because both DUEs are jointly associated with solely one BS. The decision of which BSs are the candidate ones for a D2D pair to associate with depends on the mean path-loss estimations (distance based) and is analyzed in the sequel.

### B. Fractional Frequency Reuse (FFR)

This paper's approach is based on the consideration of FFR as an interference-limiting method that can be considered for both uplink and downlink communication in cellular networks. With this method, each cell is partitioned in geographical segments with different frequency reuse factors, characterized by different proportions of bandwidth and available radio resources. For each cell, two spatial segments are included, the so-called inner and outer cell regions, where in most of the cases the bandwidth availability for the inner region is twice the size of the outer. In [33], enhanced soft FFR (s-FFR) is considered as a promising key technology to achieve large-scale cooperative radio resource management (LS-CRRM) in future 5G networks due to its interference controllability attribute, especially for cell-edge users. In this scheme, users that can be supported by small cells and are characterized by non-strict QoS requirements share the same channel resources with users served by a macro cell BS, whereas the rest of the users are assigned with different resources. Motivated by it, we further consider the integration of D2D communications and apply a differentiated FFR scheme where D2D users will be assigned resources from a resource block (RB) pool that its content depends on the DUEs' location and the respective BSs to serve them [34]. A frequency reuse factor (FRF) of three is used for the cell-edge (outer) areas, as depicted in Fig. 1. With this modelling, cellular UEs (CUEs) that are located in the inner cell areas can use a segment of the whole frequency band ( $F1$ ), whereas outer cell CUEs can use one third of the remainder ( $F2$ ,  $F3$  or  $F4$ ). As mentioned before, the available RB pool for users located in inner region ( $N_{Inner}$ ) is proportional to the interior-area radius and is twice the size of the pool corresponding to the cell-edge users ( $N_{Outer}$ ) [35]. However, the differentiation of this FFR scheme concerns the D2D communication links. Compared to the conventional FFR (s-FFR) that is applied for CUEs, if D2D UEs are located in cell inner region, they can utilize resources from the frequency sub-bands that cellular users do not use within the same cell (e.g. in Fig. 1, a D2D link located in the inner region of cell 3 can be assigned resources only from sub-bands  $F2$  &  $F3$ ). On the other hand, if DUEs are located in a cell's outer area, they can utilize resources from all available spectrum except for the sub-band that can be exploited by cellular users in identical cell outer area (again, for a cell-edge D2D link in cell 3, the sub-bands  $F1$ ,  $F2$  &  $F3$  would compose its available RB pool).

With this interference-aware method, the inner-region D2D and cellular transmissions take place in orthogonal channels. However, intra-cell interference still exists but can only be exerted from outer-cell DUEs and inner-cell CUEs (and vice versa) or multiple DUEs that might utilize the same resource. Regarding inter-cell interference, outer-cell D2D links can experience interference by adjacent outer-cell CUEs. The way

TABLE I  
RESOURCE AVAILABILITY PER CELL BASED ON DIFFERENTIATED FFR

Cell id ( $b$ )	Inner-region D2D	Outer-region D2D
$b = 1$	$\{F_3\} \cup \{F_4\}$	$\{F_1\} \cup \{F_3\} \cup \{F_4\}$
$b = 2 \cdot i^*$	$\{F_2\} \cup \{F_4\}$	$\{F_1\} \cup \{F_2\} \cup \{F_4\}$
$b = 2 \cdot i + 1$	$\{F_2\} \cup \{F_3\}$	$\{F_1\} \cup \{F_2\} \cup \{F_3\}$

\* $i = 1, 2, 3, \dots$

to efficiently allocate the resources in an interference-aware manner will be presented in Section IV.

### C. Basic notations and definitions

We consider a set of BSs  $\mathcal{B} = \{b_1, b_2, \dots, b_{|\mathcal{B}|}\}$  and a set of D2D links  $\mathcal{L} = \{l_1, l_2, \dots, l_{|\mathcal{L}|}\}$  randomly distributed in a hexagonal multi-cell topology. The  $|\cdot|$  notation declares the cardinality of a set. Each BS  $b \in \mathcal{B}$  has a pool of available resource blocks, denoted as  $\mathcal{K}_b$ , of  $K_b$  elements. All BSs have the same number of resources  $K_b$ . However, the available RB pool for each  $b \in \mathcal{B}$  is different and depends on the discussed FFR scheme, as shown in TABLE I. In the context of this work, each association of a D2D link with a BS implies the occupation of a single RB. As a consequence, the total number of D2D associations with a specific BS will be equal to the number of RBs allocated by the same BS.

Let us further define by  $c_{lb}$  the *cost* of a D2D link  $l$  connected to BS  $b$ ; this can be considered as the average path-loss (distance-based) of connecting both nodes  $n_1$  and  $n_2$  of a D2D pair at the same BS and is estimated as follows:

$$c_{lb} = \frac{PL_{n_1,b} + PL_{n_2,b}}{2} \quad (3)$$

where  $PL_{n_i,b} = 128.1 + 37.6 \log_{10} r_{n_i,b}$  is the path-loss (in dB) between BS  $b$  and DUE  $n_i$ , for  $i = 1, 2$ . In this formula,  $r_{n_i,b}$  is the DUE-BS distance (in kilometres). For current and emerging cellular networks, where connected DUEs might have subsequent direct (D2D) and cellular UL/DL transmissions, this cost metric represents the need to stay "as close as possible" to the serving BS to support both communication types that can happen in short and sequential time epochs. Furthermore, because we focus on the UL, a user's association with a BS should be preferably decided by its estimated path-loss to it and not by the traditional DL received signal-based criterion in cellular networks [23]. To this end, and in order to ensure reduced signaling overhead, the D2D links that are characterized by association ambiguity (i.e. two nodes should be normally associated with different BSs) are coupled with the BS that achieves the minimum average path-loss.

In order to formulate the problem of the D2D cell association, the following binary variable needs to be defined:

$$y_{lb} = \begin{cases} 1, & \text{if link } l \text{ is connected to BS } b \\ 0, & \text{otherwise.} \end{cases} \quad (4)$$

The sequence of the  $y_{lb}$  values will construct a vector that defines the solution of the ILP optimization settings that will follow. This vector can be represented as:

$$\mathbf{y} = [y_{11}, y_{21}, \dots, y_{|\mathcal{L}|1}, \dots, y_{1|\mathcal{B}|}, \dots, y_{|\mathcal{L}||\mathcal{B}|}]^T. \quad (5)$$

It is clear that only  $|\mathcal{L}|$  values of it can equal to one due to the sole association of a D2D link with only one BS.

#### D. Joint cell association and resource allocation

Herein, the joint cell association and resource allocation problem is introduced. As it will be detailed in the sequel, the first objective is to balance the number of connections in order to achieve a resource efficient orchestration and constitutes the cell association part of the problem. On the other hand, D2D sum rate maximization is the second objective and aims at optimizing the resource allocation for D2D communications.

In continuity of the definitions presented in the above subsection, we further denote with  $R_{lbk}$  the achievable throughput for link  $l$  that associates with BS  $b$  and utilizes the RB  $k$ , and also define  $x_{lbk}$  as a binary decision variable that indicates whether the link  $l$ , associated with BS  $b$ , is assigned with RB  $k$  or not. Then, the joint problem can be formulated as follows:

$$\min \left\{ \sum_{b \in \mathcal{B}} \left( \sum_{l \in \mathcal{L}} y_{lb} \right)^2 ; - \sum_{l \in \mathcal{L}} \sum_{b \in \mathcal{B}} \sum_{k \in \mathcal{K}} R_{lbk} x_{lbk} \right\} \quad (6)$$

$$\text{s.t. } \sum_{b \in \mathcal{B}_l} y_{lb} = 1, \forall l \in \mathcal{L} \quad (6a)$$

$$\sum_{l \in \mathcal{L}} y_{lb} \leq K_b, \forall b \in \mathcal{B} \quad (6b)$$

$$\sum_{b \in \mathcal{B}_l} c_{lb} y_{lb} \leq c_{th}, \forall l \in \mathcal{L} \quad (6c)$$

$$\sum_{b \in \mathcal{B}_l} \sum_{k \in \mathcal{K}} R_{lbk} x_{lbk} \geq R_{th}, \forall l \in \mathcal{L} \quad (6d)$$

$$\sum_{b \in \mathcal{B}_l} \sum_{k \in \mathcal{K}} x_{lbk} = 1, \forall l \in \mathcal{L} \quad (6e)$$

$$\sum_{k \in \mathcal{K}_b} x_{lbk} = y_{lb}, \forall l \in \mathcal{L}, \forall b \in \mathcal{B} \quad (6f)$$

$$y_{lb}, x_{lbk} \in \{0, 1\}, \forall l \in \mathcal{L}, \forall b \in \mathcal{B}, \forall k \in \mathcal{K}, \quad (6g)$$

where  $\mathcal{B}_l$  is the set of candidate BSs to be associated with the link  $l$ . Each D2D pair cannot be associated with whichever BS. Constraints (6a) require that each link  $l$  will be associated with only one of the BSs that belongs to the  $\mathcal{B}_l$  set. Inequality constraints (6b) are introduced to avoid any resource availability violation for each BS  $b$ . (6c) accounts for the cost values (eq. (3)) not to be above a pre-defined cost threshold  $c_{th}$ . Constraint (6d) accounts for satisfying each D2D link's rate threshold, whereas (6e) means that each D2D link  $l$  can be associated with only one BS and be assigned with only one RB. Then, (6f) signifies that a link  $l$  that is associated with a BS  $b$  can be only assigned with a RB  $k$  that stems from the BS's  $b$  available resource pool (i.e.  $\mathcal{K}_b$ ). Finally, (6g) ensures the binary assignment of the  $\mathbf{y}$  and  $\mathbf{x}$  vector's values.

Due to the reusability of a RB by potentially more than one D2D pair as well as the existence of multiple D2D links, this problem falls into the nature of mixed integer non linear programming (MINLP) optimization problems that are hard to be solved in polynomial time and optimal solution

cannot be acquired unless a number of constraints' relaxation applies. It is also worth pointing out that cell association and RB allocation take place in time scales that can differ multiple orders of magnitude and therefore, looking at this problem at the time domain, it can be concluded that in a real-world applications it is a natural approach to decompose the problem as presented in later sections. To this end, and in order to reduce the complexity and hardness, we proposed the decoupling of the joint problem into two sub-problems; first, we solve the ILP cell association problem, and then, following the produced D2D association pattern, we apply the low-complexity resource allocation heuristic algorithm.

### III. D2D CELL ASSOCIATION PROBLEM DESCRIPTION

A set of cell association-based optimization problems for DUEs will be herein presented. The basic idea is to introduce an optimal framework for D2D links that considers spectrum efficiency as well as interference restriction in a multi-cell network. To this end, in the following subsections we proceed with proposing a number of different D2D cell association formulations with different objective functions. We anticipate that, according to varying network traffic scenarios, this set of optimization problems can be considered as an add-on feature for the network operator to be able to choose among the different association policies.

#### A. Resource-aware Cell Association Optimization: MOCA-I

1) *Motivation:* Cell association is highly correlated with the ability of the network infrastructure to accommodate a significant number of connections simultaneously. However, the integration of D2D paradigm in emerging wireless networks urges network operators to contemplate how the DUEs' association problem should be addressed in order to efficiently exploit its resource reuse ability and, thus, avoid any resource blocking by dedicating part of the spectrum for it which is done in overlaid D2D communications. On top of this, interference exerted to (from) the cellular communications from (to) D2D links and among multiple D2D transmissions needs to be taken into consideration. This means that, if the limited available resources provided by a macro BS are potentially over-utilized by multiple D2D links in a cell, this can bring in undesired interference patterns. For this reason, D2D user association should attain a balanced D2D-based link orchestration with respect to resource efficiency.

2) *Problem formulation:* This problem can be mathematically formulated as follows:

$$\min \sum_{b \in \mathcal{B}} \left( \sum_{l \in \mathcal{L}} y_{lb} \right)^2 \quad (7)$$

$$\text{s.t. } \sum_{b \in \mathcal{B}_l} y_{lb} = 1, \forall l \in \mathcal{L} \quad (7a)$$

$$\sum_{l \in \mathcal{L}} y_{lb} \leq K_b, \forall b \in \mathcal{B} \quad (7b)$$

$$\sum_{b \in \mathcal{B}_l} c_{lb} y_{lb} \leq c_{th}, \forall l \in \mathcal{L} \quad (7c)$$

$$y_{lb} \in \{0, 1\}, \forall l \in \mathcal{L}, \forall b \in \mathcal{B}. \quad (7d)$$

The above constraints were detailed in II-D. We note that this is in essence a non-linear integer optimization problem which is not suitable to be solved via powerful available toolboxes on integer linear mathematical programming. This problem can be then re-formulated as an integer linear program if viewed as a max-min optimization problem in the way we detail below:

$$\max z \quad (8)$$

$$\text{s.t. } z \leq \sum_{l \in \mathcal{L}} y_{lb}, \forall b \in \mathcal{B} \quad (8a)$$

$$\sum_{b \in \mathcal{B}_l} y_{lb} = 1, \forall l \in \mathcal{L} \quad (8b)$$

$$\sum_{l \in \mathcal{L}} y_{lb} \leq K_b, \forall b \in \mathcal{B} \quad (8c)$$

$$\sum_{b \in \mathcal{B}_l} c_{lb} y_{lb} \leq c_{th}, \forall l \in \mathcal{L} \quad (8d)$$

$$y_{lb} \in \{0, 1\}, \forall l \in \mathcal{L}, \forall b \in \mathcal{B}. \quad (8e)$$

This optimization problem is an ILP problem that due to the unimodular property of its inequality matrix (i.e. determinant of every square sub-matrix equals to 1) can be solved efficiently, since it resembles the computational complexity of the corresponding linear (fractional) program. Regarding  $z$ , this variable is a positive integer number and represents the minimum number of D2D-BS associations in a multi-cell deployment. Thus, the obtained decision vector of the aforementioned optimization problem is  $[y; z]$ .

It was shown in the authors' previous work that simply minimizing the defined overall cost doesn't introduce significant gains compared to cost-aware heuristic methods [25]. It was observed that even though the performance gap is slightly increasing for higher congestion levels, this gain is negligible. Thus, a multi-cell based resource aware optimization on top of retaining the cost below a certain level (eq. (8)) is much more meaningful for the network's welfare.

### B. Joint connectivity cost & RB reuse optimization: MOCA-II

1) *Motivation:* With the advent of the data-driven era and the ongoing user densification, the probability of two users to communicate directly increases. Especially in mass events, such as concerts or football games, where the incoming data requests are highly correlated to the event, the need to support multiple local communications arises. Due to the limited channel resources, and in order to support these multiple connections, some of the available resources might be reused by multiple links within a cell. This can be translated to interference effects among the users that use the same RBs. To this end, an optimization problem is proposed as pertain to the issue of resource optimization usage and, more specifically, to efficiently minimize the overall RB reuse levels for highly congested scenarios. We provide D2D-BS association, in parallel with RB allocation, so that the reuse rate of RBs (which are assigned based on the differentiated FFR method) is potentially minimized.

2) *Problem formulation:* We formulate the aforementioned problem as a bi-objective optimization setting. First, we define the following decision variable:

$$\tau_{kb} = \begin{cases} 1, & \text{if RB } k \text{ of BS } b \text{ is used} \\ 0, & \text{otherwise.} \end{cases} \quad (9)$$

Additionally, we denote with  $\rho_{kb}$  an index that captures how many times a RB  $k$  is assigned by the BS  $b$ . Based on the above definitions, we formulate the following optimization problem which provides optimal D2D cell association with the prospect of minimizing the reuse of RBs in the network:

$$\min \left\{ \sum_{l \in \mathcal{L}} \sum_{b \in \mathcal{B}} c_{lb} y_{lb} ; \sum_{k \in \mathcal{K}} \sum_{b \in \mathcal{B}} \rho_{kb} \tau_{kb} \right\} \quad (10)$$

$$\text{s.t. } \sum_{b \in \mathcal{B}_l} y_{lb} = 1, \forall l \in \mathcal{L} \quad (10a)$$

$$\sum_{l \in \mathcal{L}} y_{lb} \leq K_b, \forall b \in \mathcal{B} \quad (10b)$$

$$\sum_{k \in \mathcal{K}} \tau_{kb} \leq K_b, \forall b \in \mathcal{B} \quad (10c)$$

$$\sum_{k \in \mathcal{K}} \tau_{kb} \leq \sum_{l \in \mathcal{L}} y_{lb}, \forall b \in \mathcal{B} \quad (10d)$$

$$\sum_{b \in \mathcal{B}_l} c_{lb} y_{lb} \leq c_{th}, \forall l \in \mathcal{L} \quad (10e)$$

$$y_{lb}, \tau_{kb} \in \{0, 1\}, \forall l \in \mathcal{L}, \forall b \in \mathcal{B}, \forall k \in \mathcal{K}. \quad (10f)$$

Following the notations used above,  $\mathcal{K}$  accounts for the set of total available resources (e.g. for a 10 MHz LTE-based system bandwidth, set  $\mathcal{K}$  contains 50 physical RBs in total, according to 3GPP specifications). However, according to the principles of the differentiated FFR scheme, each BS  $b$  provides a subset  $\mathcal{K}_b$  of the total available resources (TABLE I). According to it and the subsection II-B analysis, each inner-region D2D pair can be assigned a channel resource out of 20 RBs, whereas for the outer-region ones the number is doubled. Hence, the resources' upper bound per cell is 40. Constraints (10a), (10b) were described in the previous subsection. Further, we note that constraints (10c) are logically redundant since they are implied by the constraints in (10d), but we include them in the formulation in order to reduce the search effort and runtime (i.e., reducing further the search space).

It has to be highlighted that the proposed technique can be used in other frequency reuse techniques (or even different frequency reuse factors) that mainly aim to address the inter-cell interference coordination problem in multi-cell networks.

### C. Joint interference-aware & resource efficient optimization: MOCA-III

1) *Motivation:* A very important issue that needs to be addressed is the potential interference developed due to the co-existence of multiple D2D pairs and CUEs. According to the applied FFR technique, a cell-edge or crossing D2D pair that associates with a BS can mainly cause interference to cellular transmission of adjacent outer-cell regions that might utilize the same resource. Similarly, during the UL session



that D2D communication is expected to happen, the D2D receiver suffers interference from the CUE that transmits to its coupled BS. Because of the limited resources for outer cellular UEs, the probability that a CUE will utilize the same resource with a neighbouring DUE becomes high. Considering that a CUE has a specified interference range constructed by its UL transmission, the possibility that a D2D link will be harmed needs to be avoided. An example is given in Fig. 4.

Especially in highly dense networks, the need to avoid immense interference scenarios is of paramount importance. By applying a joint optimization framework that regards not only the resource availability but also the existence of potential cellular interferers, this can entail better system throughput and overall performance improvement in the long run.

2) *Problem formulation:* We introduce a penalty factor  $\vartheta_{lb}$  that represents the number of cellular users that can be interfering with the D2D link  $l$ . For each  $l \in \mathcal{L}$  which has a set  $\mathcal{B}_l$  of candidate BSs for association, this penalty factor parameter is assigned with a value that equals to the number of CUEs that are able to harm the D2D pair  $l$  (Fig. 4). For ease of comprehension, we first formulate it as a solely interference-aware optimization problem as follows:

$$\min \sum_{l \in \mathcal{L}} \sum_{b \in \mathcal{B}} \vartheta_{lb} y_{lb} \quad (11)$$

$$\text{s.t.} \quad \sum_{b \in \mathcal{B}_l} y_{lb} = 1, \quad \forall l \in \mathcal{L} \quad (11a)$$

$$\sum_{l \in \mathcal{L}} y_{lb} \leq K_b, \quad \forall b \in \mathcal{B} \quad (11b)$$

$$\sum_{b \in \mathcal{B}_l} c_{lb} y_{lb} \leq c_{th}, \quad \forall l \in \mathcal{L} \quad (11c)$$

$$y_{lb} \in \{0, 1\}, \quad \forall l \in \mathcal{L}, \quad \forall b \in \mathcal{B}. \quad (11d)$$

Then, by encapsulating the problem of orchestrating the D2D links in a way that overall resource savings can be achieved (problem (7)) to the above setting, **we introduce the following bi-objective optimization solution:**

$$\min \left\{ \sum_{b \in \mathcal{B}} \left( \sum_{l \in \mathcal{L}} y_{lb} \right)^2 ; \sum_{l \in \mathcal{L}} \sum_{b \in \mathcal{B}} \vartheta_{lb} y_{lb} \right\} \quad (12)$$

$$\text{s.t.} \quad \sum_{b \in \mathcal{B}_l} y_{lb} = 1, \quad \forall l \in \mathcal{L} \quad (12a)$$

$$\sum_{l \in \mathcal{L}} y_{lb} \leq K_b, \quad \forall b \in \mathcal{B} \quad (12b)$$

$$\sum_{b \in \mathcal{B}_l} c_{lb} y_{lb} \leq c_{th}, \quad \forall l \in \mathcal{L} \quad (12c)$$

$$y_{lb} \in \{0, 1\}, \quad \forall l \in \mathcal{L}, \quad \forall b \in \mathcal{B}. \quad (12d)$$

Without loss of generality, the two objectives are assumed to be equally important and an efficient balance between them is requested. Note that the first objective should be transformed in accordance with (8) to linearize the optimization problem.

The aim is to apply the weighted-sum (or scalarization [36]) method that combines two objectives into a joint, single-objective function. Let us first denote with  $\mathbf{s}$  a decision vector

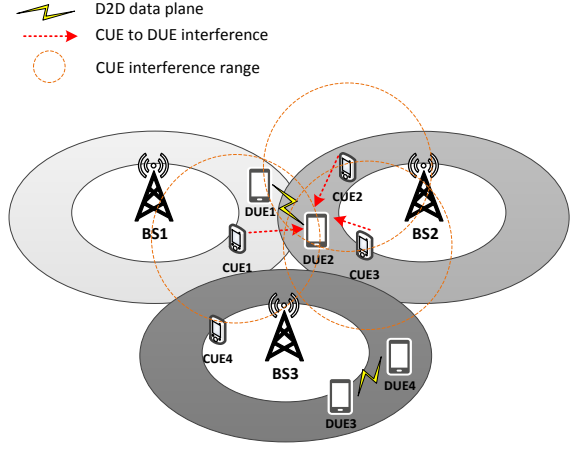


Fig. 4. CUEs to DUEs interference depiction. Possible association of the D2D link with BS1 will give bigger probability of interfering with a cellular user that is located in the serving area of BS2.

for this optimization problem. For the formulation provided above (problem (12)), we denote by  $f_1(\mathbf{s})$  the function that corresponds to the resource-aware balancing objective and by  $f_2(\mathbf{s})$  the interference-aware part of the bi-objective problem. In order to make the joint objective tractable, the following transformations must be applied:

$$f_{1trans}(\mathbf{s}) := \frac{f_1(\mathbf{s})}{\max(K_b)} \in (0, 1], \quad (13)$$

$$f_{2trans}(\mathbf{s}) := \frac{f_2(\mathbf{s})}{\sum \max(I^T)} \in (0, 1], \quad (14)$$

where  $\max(K_b)$  in equation (13) is the maximum number of available RBs for all participating BSs. Also, in (14),  $I$  is the matrix of size  $|\mathcal{L}| \times |\mathcal{B}|$ , where each element  $I_{lb}$  contains information about the number of the potential cellular interferers for the receiver of D2D link  $l$  in case it connects to a BS  $b$ ; the denominator in equation (14) can be stepwise described as follows:

$$I = \begin{pmatrix} \vartheta_{11} & \vartheta_{12} & \cdots & \vartheta_{1|\mathcal{B}|} \\ \vartheta_{21} & \vartheta_{22} & \cdots & \vartheta_{2|\mathcal{B}|} \\ \vdots & \vdots & \ddots & \vdots \\ \vartheta_{|\mathcal{L}|1} & \vartheta_{|\mathcal{L}|2} & \cdots & \vartheta_{|\mathcal{L}||\mathcal{B}|} \end{pmatrix}, \quad (15)$$

$$\max(I^T) = \begin{pmatrix} \max(\vartheta_{11}, \vartheta_{12}, \dots, \vartheta_{1|\mathcal{B}|}) \\ \max(\vartheta_{21}, \vartheta_{22}, \dots, \vartheta_{2|\mathcal{B}|}) \\ \vdots \\ \max(\vartheta_{|\mathcal{L}|1}, \vartheta_{|\mathcal{L}|2}, \dots, \vartheta_{|\mathcal{L}||\mathcal{B}|}) \end{pmatrix}^T. \quad (16)$$

It equals to the summation of the maximum interferers for each D2D link when it couples with one of the candidate BSs.

Considering the above properties and by linearizing the first objective as already shown, the problem is re-formulated to adapt to the weighted sum optimization technique. The general form of the weighted sum problem is as follows:

$$\min \sum_{i=1}^N w_i f_{i trans}(\mathbf{s}) \quad (17)$$

$$\begin{aligned}
\text{s.t. } & \sum_{i=1}^N w_i = 1 & (17a) \\
& w_i \geq 0, \forall i = 1, \dots, N & (17b) \\
& \mathbf{s} \in S & (17c) \\
& \mathbf{s} \leftarrow \text{integer vector.} & (17d)
\end{aligned}$$

Constraint (17a) concerns the weights of the two ( $N = 2$ ) objective functions and enforces their summation to be equal to one, which is a common practice in weighted sum approaches. Additionally,  $S$  is the general set of constraints that needs to be satisfied and is detailed in the formulation below. The acquired decision vector solution  $\mathbf{s}$  of this optimization problem will consist of the decision variable  $\mathbf{y}$  as well as the  $z$ -constrained variable (as defined for problem (8)); it can be mathematically represented as  $\mathbf{s} = [\mathbf{y}; z]$ . After injecting the equations (13) and (14), the final formulation of this problem is obtained:

$$\begin{aligned}
\min & \left[ \underbrace{-w_1 \frac{z}{\max(K_b)}}_{f_{1trans}} + \underbrace{w_2 \frac{\sum_{l \in \mathcal{L}} \sum_{b \in \mathcal{B}} \vartheta_{lb} y_{lb}}{\sum \max(I^T)}}_{f_{2trans}} \right] & (18) \\
\text{s.t. } & z \leq \sum_{l \in \mathcal{L}} y_{lb}, \forall b \in \mathcal{B} & (18a) \\
& \sum_{b \in \mathcal{B}_l} y_{lb} = 1, \forall l \in \mathcal{L} & (18b) \\
& \sum_{l \in \mathcal{L}} y_{lb} \leq K_b, \forall b \in \mathcal{B} & (18c) \\
& \sum_{b \in \mathcal{B}_l} c_{lb} y_{lb} \leq c_{th}, \forall l \in \mathcal{L} & (18d) \\
& y_{lb} \in \{0, 1\}, \forall l \in \mathcal{L}, \forall b \in \mathcal{B} & (18e) \\
& \sum_{i=1}^N w_i = 1. & (18f)
\end{aligned}$$

#### IV. D2D RESOURCE ALLOCATION

In this section, the second step of our two-stage approach is presented. Herein, an iterative randomized resource allocation (i-RRA) scheme for D2D communications based on the differentiated FFR is devised. Before introducing the RA algorithm, the following assumptions need to be considered. We apply the fractional power control algorithm ([37]) that sets the transmit power of a user  $u$  associated with BS  $b$  according to:

$$P_u = \min\{P_{\max}, 10 \log_{10}(M) + P_0 + \alpha L_{ub}\}, \quad (19)$$

where  $P_{\max}$  is the maximum transmit power of the device (24 dBm),  $M$  is the number of physical RBs (PRBs) assigned to the device,  $P_0$  is a normalized power value (in dB),  $\alpha$  is the path-loss compensation factor and  $L_{ub}$  is the path-loss between the transmitting UE  $u$  and its serving (associated) cell  $b$ . User index  $u$  corresponds to either a cellular UE or a D2D transmitter transmitting during the UL.

We recall from paragraph II-B that in a multi-cell scenario, due to the concurrent cellular and D2D transmissions, severe interference might deteriorate the rate performance of both user types. CUEs can be harmed by multiple D2D active transmissions that utilize the same resource as well as by adjacent

cells' cellular transmissions. On the other hand, D2D receivers suffer interference not only from other DUEs that transmit on the same channel but also from cellular transmissions of all cells. In order to calculate the achievable rate for both communication types, the received signal-to-interference-plus-noise ratio (SINR) at a D2D receiver (direct communication) and a BS (cellular communication) needs to be estimated:

$$\gamma_{ij} = \frac{P_i G_{ij}}{\sum_{q=1}^{|Q_j|} P_q G_{qj} + \sigma^2}. \quad (20)$$

In the case of cellular UL transmission,  $i$  corresponds to a transmitting CUE and  $j$  translates to the associated with user  $i$  BS. For a D2D pair,  $i$  is the transmitter and  $j$  the receiver. In the nominator,  $G_{ij}$  stands for the link gain in  $i \rightarrow j$  transmission and  $P_i$  is the transmission power estimated according to eq. (19). In the denominator, the first factor represents the sum of the interference power from the other interfering signals. In detail,  $Q_j$  is the set of interfering nodes that utilize the same channel allocated for the  $i \rightarrow j$  transmission,  $G_{qj}$  is the channel gain from interferer  $q$  to receiver  $j$ , and  $P_q$  is the transmission power of interferer  $q \in Q_j$ . Finally,  $\sigma^2$  denotes the background/thermal noise power. Note also that, the mentioned link gains encapsulate slow channel fading (shadowing) impairments, with a shadowing standard deviation of 8 dB for both communication types.

According to the previous definitions, the received SINR for each transmission can be then mapped to achievable rate by using the Shannon capacity formula:

$$R_{ij} = B_{RB} \log_2(1 + \gamma_{ij}), \quad (21)$$

with  $B_{RB}$  being the RB bandwidth (180 KHz). Hence, the network's aggregate throughput is the summation of the achievable rates of all D2D and cellular communications.

##### A. Iterative Randomized RA algorithm (i-RRA)

We propose a low-complexity, iterative randomized algorithm which runs in a semi-centralized manner as follows: first, the cellular users of each cell are initially assigned with orthogonal RBs, depending on the area they are located in (inner or outer). Secondly, assuming that  $\mathcal{N}$  available RBs exist in the scope area, each BS will randomly allocate one RB per associated D2D pair according to the aforementioned FFR allocation logic. This RB will be then subtracted from the corresponding to each cell available RB pool. In case that all RBs are occupied (highly dense D2D scenarios), a cellular resource can be reused by more than one D2D link. This implementation will run for up to a designated number of iterations  $M$ . Then, the BSs cooperatively opt the best allocation pattern among all. The criterion for finally choosing the best resource allocation pattern is the total network throughput, estimated as the aggregation of cellular and D2D rates for all cells. The algorithmic steps are given in Algorithm 1.

The proposed algorithm's nature falls within the category of "embarrassingly" parallel problems because iterations of the algorithm to explore the search space can be executed without requiring any communication between them [38]. Its

**Algorithm 1: i-RRA ALGORITHM**

**Data:** CUEs and DUEs' location coordinates,  
 $C_b$ : set of CUEs in cell  $b$ ,  
 $\mathcal{L}_b$ : set of D2D links associated with cell  $b$  (input from MOCA framework),  
 $\{N_{\text{Inner}}^b\}$ : inner-region available RBs in each cell  $b$ ,  
 $\{N_{\text{Outer}}^b\}$ : outer-region available RBs in each cell  $b$ ,  
 $M$ : number of iterations.

```

for  $b := 1$  to  $|\mathcal{B}|$  do
  • Allocate one unused (orthogonal) RB  $\forall c \in C_b$ 
  from  $\{N_{\text{Inner}}^b\}$  or  $\{N_{\text{Outer}}^b\}$  depending on its location.
end
for  $m := 1$  to  $M$  do
  for  $b := 1$  to  $|\mathcal{B}|$  do
    •  $S_b \leftarrow \{N_{\text{Inner}}^b\} \cup \{N_{\text{Outer}}^b\}$ .
    foreach  $l \in \mathcal{L}_b$  do
      • Randomly allocate one RB  $k$  to  $l \in \mathcal{L}_b$  from
      the corresponding  $S_b$  available RB pool.
      • Subtract assigned RB from the available
      pool:  $S_b \leftarrow S_b \setminus \{k\}$ .
    end
  end
  • Compute  $\forall l \in \mathcal{L}$  the achievable rate  $R_l$  and  $\forall c \in \mathcal{C}$ 
  the achievable rate  $R_c$ .
  •  $R_{\text{total}}(m) \leftarrow \sum_{b=1}^{|\mathcal{B}|} \left( \sum_{c=1}^{|\mathcal{C}_b|} R_c + \sum_{l=1}^{|\mathcal{L}_b|} R_l \right)$ .
end
 $T = \max\{R_{\text{total}}\} \rightarrow$  Maximum estimated Aggregate
Throughput

```

computational complexity is  $\mathcal{O}(M)$ , which means that it only increases linearly with the number of iterations  $M$ . To even reduce more the runtime, parallel processors can be used to distribute the computational complexity of running the algorithm for a big number of iterations.

## V. NUMERICAL INVESTIGATIONS

For the realization of this work, D2D links and CUEs are uniformly distributed in both seven-hexagonal cells and PPP-Voronoi based deployments. In the hexagonal case, 30 CUEs are deployed per cell; 20 of them are located in each cell's inner region whereas the rest in the cell-edge area. Also, a key premise is that one RB will be allocated to each D2D and cellular link. We follow the LTE-Advanced principles and utilize a 10 MHz channel bandwidth that translates to 50 available RBs in all cases. The basic simulation parameters, similar to EU FP7 METIS project [39], are listed in TABLE II. The results derive from Monte Carlo simulations in MATLAB.

For the performance evaluation of the proposed optimization framework a cost-based heuristic (CbH) cell association technique for D2D UEs is devised. This method greedily associates each D2D pair to the BS that averagely provides the best channel conditions to the two linked DUEs (Algorithm 2). Even though this method optimizes the coupling of the distributed D2D links according to path-loss based equation (3), it does not consider the BSs' limited resource availability

TABLE II  
SIMULATION/NUMERICAL PARAMETERS

Parameter	Value
Hexagonal cell radius ( $d$ )	400 m
Number of macro cells	7
Number of CUEs per hexagonal cell	30
Cellular path-loss model ( $PL_{\text{CUE}}$ ) [40]	$128.1 + 37.6 \log_{10} d$
D2D path-loss model ( $PL_{\text{D2D}}$ ) [40]	$148 + 40 \log_{10} d$
Max D2D link range ( $l_{n_1, n_2}$ )	100 m
Maximum UE transmission power ( $P_{\text{max}}$ )	24 dBm
Shadowing standard deviation	8 dB
Noise power spectral density	-174 dBm/Hz
System bandwidth ( $BW$ )	10 MHz

which might lead to imbalanced cell association issues (thus, cases of over-loaded cells) in the long run. Basically, this algorithm runs in a centralized, sorted manner by sequentially associating each D2D link with the ideal BS to serve it. To avoid any over-utilization of the BSs, if all the available RBs of a BS get occupied, the transmission of the respective DUEs is regulated from a competing BS that is less utilized.

**Algorithm 2: COST-BASED HEURISTIC (CbH)**

**Data:** DUEs' location coordinates, cost matrix  
 $\mathbf{C} \in \mathbb{R}_{+}^{|\mathcal{L}| \times |\mathcal{B}|}$ , capacity vector  $\mathbf{K} \in \mathbb{Z}_{+}^{1 \times |\mathcal{B}|}$ .

```

 $l = 1$ ;
while  $l \leq |\mathcal{L}|$  do
  • Find D2D link with minimum cost ( $\min\{\mathbf{C}\} = c_{i,j}$ ,
  where  $i$  is the row (D2D link id) and  $j$  is the
  column (BS id)).
  if ( $c_{i,j} \leq c_{th}$  &  $K_j \neq 0$ ) then
    • Associate link  $i$  with BS  $j$ .
    •  $K_j = K_j - 1$ ;
    •  $c_{i,j} = \text{Inf}$ ;  $c_{i,(1:|\mathcal{B}|})} = \text{Inf}$ ;  $\rightarrow$  all  $i$ -th row
    values cannot be picked...
  else
    if ( $c_{i,j} \leq c_{th}$  &  $K_j == 0$ ) then
      •  $c_{(1:|\mathcal{L}|),j} = \text{Inf}$ ;  $\rightarrow$  all  $j$ -column
      elements cannot be picked...
      • Find minimum cost for  $i$ -th link and for
       $\{\mathbf{K} \setminus K_j\}$ .
      • Update cost matrix ( $\mathbf{C}$ ) and capacity vector
      ( $\mathbf{K}$ ) accordingly.
    else
      • Link  $i$  cannot be associated (will associate
      in subsequent time epoch).
    end
  end
   $l = l + 1$ ;
end

```

As shown in our work in [25], the gain that is achieved by minimizing the previously defined cost compared to CbH is negligible for different, **randomly chosen** network congestion levels (please refer to problem (6) and Fig. 4 of [25] for further details). By saying network congestion level we imply the number of already existing associations (differently, occupied RBs) for all BSs in the topology. The most distinctive gain is met for high-traffic scenarios (especially when the overall

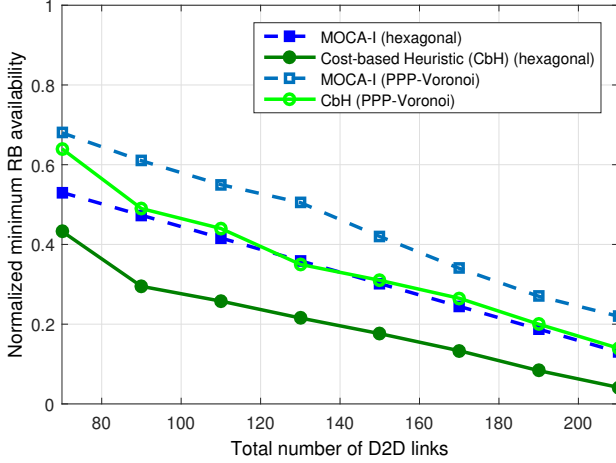


Fig. 5. Normalized minimum RB availability for MOCA-I and CbH techniques in relation to the number of D2D links.

congestion level is over 90%) where the optimization solver behaves 3.2% better in terms of association cost.

#### A. Evaluation on resource-aware CAS optimization (III-A)

The overall picture though is very different and the gains are significant when a form of D2D control and resource utilization balancing is considered. For this simulation setting, we retain the same  $K_b$  values for each  $b \in \mathcal{B}$  to be equal to the number of available D2D resources (i.e. 40) and assume that the (8) optimization problem is solved for each instant and for the different number of D2D links. Starting from 70 D2D links in the hexagonal grid, for each different case another 20 is added and each BS associates with a number of D2D links, according to (8). As mentioned before, each D2D link is then assumed to be allocated with one RB to satisfy its transmission needs. 1000 Monte Carlo simulations are executed to produce a statistical comparison of this problem's performance with the CbH method. Fig. 5 presents the normalized minimum RB availability that is achieved by using these two methods in the cases of hexagonal and PPP-Voronoi based cell layouts. By normalized minimum RB availability we mean the percentage of unallocated RBs among the deployed BSs that basically translates to the most utilized BS. On average, and for the case of hexagonal multi-cell environments, 12% more resources are available when using MOCA-I. In the same figure, a statistical maximum 19% of minimum RB availability is shown for the case of 90 D2D links. Compared to it, in random deployment scenarios where the BSs' locations follow PPP modeling, the estimated RB availability is distinctly higher. This can be explained by the randomness of the cell shapes that, in some cases, allows for having multiple cell-edge links in the borders of more than two cells, and consequently, more BSs are candidates for association with them. According to the Monte Carlo based statistics, MOCA-I achieves an almost 10% increase resource availability, compared to CbH method, and a peak performance gain of 15% in the case of 130 links.

#### B. Evaluation on joint connectivity cost & RB reuse optimization (III-B)

For this case study, we focus on high-congestion network episodes, where some resources have to be inevitably reused for more than one D2D pair within the network. Without loss of generality, we assume that each available RB per BS is assigned with an integer value that is randomly picked (from  $[0, 2]$ ) and indicates the number of times this RB is already used. Regarding the bi-objective optimization setting (problem (10)) described in subsection III-B, the first objective function is the minimization of the path-loss based cost that we proved is only slightly better compared to the CbH method. Hence, we solve this problem for the case of RB reuse avoidance optimization (second objective function) and for highly dense scenarios. To this end, Fig. 6 proves that for different traffic cases, this solver achieves better performance compared to an average utilization agnostic method that assigns resources randomly picked from the available pool of RBs. To be more specific considering the latter, it does not take into account the existing RB reuse cases; in contrast, it randomly gets allocated with a random resource depending on the BS it is associated with. On the other hand, we also consider the worst case where the under study D2D links would be assigned with the over-utilized RBs. As depicted, for example in the case of hexagonal deployment, the proposed method succeeds in utilizing less used RBs and outperforms the worst case as well as the average utilization agnostic case in a percentage of 45% and almost 28% over-utilization avoidance gain, respectively. Specifically, this performance gain can be depicted in the same figure for the case of more than 60% of overall network congestion. We note that similar behavior is observed for more congested instances (i.e.  $> 70\%$  and  $> 80\%$ ) where the achieved gain remains significant. It has to be also noted that, because the number of distributed D2D links as well as the input matrix  $\rho$  (already assigned RBs) are the same for both hexagonal and PPP-Voronoi tessellation layouts, the differences in terms of RB over-utilization are negligible between each other.

#### C. Evaluation on joint interference-aware & resource efficient optimization (III-C)

The proposed problem (12) aims at efficiently performing resource-aware balancing while at the same time taking into account the existence of potential cellular interferers to the D2D communications. In that sense, the interference-aware part adds a useful decision-making dimension to the optimization setting and mainly relates to statistical chance of a link to interfere with a CUE. In essence, it chooses the association of a D2D link with the BS that will result in the least probability of interfering with a closely located CUE. Fig.4 represents the interference region of a CUE (orange-dashed circular area in the figure) as the area under which cellular users might interfere with a DUE receiver. In specific, this area can be specified by the transmitting CUE's location (centre of the circle) and a radius that is defined as the range of the interference. For approximation, the interference range for each CUE can vary and can be considered as the multiplication

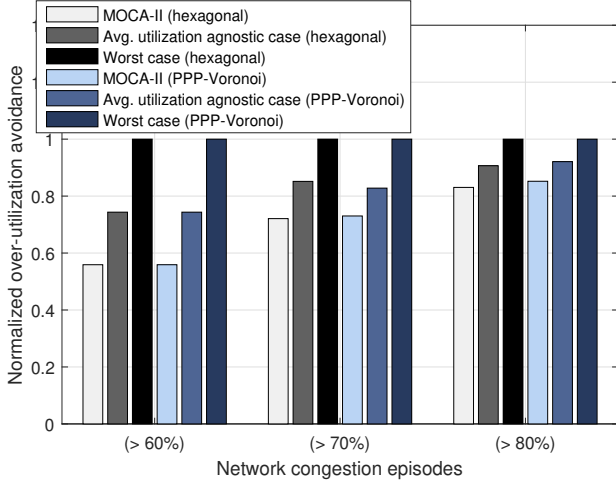


Fig. 6. Normalized RB over-utilization avoidance optimization compared to average utilization agnostic and worst case scenarios.

of the respective cellular link range with a random variable  $\beta \geq 1$  ([41]). Without loss of generality, we consider an upper limit for this variable and assume that  $\beta \in [1, 2]$ . By considering uniform distribution for both CUEs and DUEs, it might be possible to have an equal number of cellular interferers for both competing BSs to associate with a D2D link. An example is shown in Fig. 7, where a cell-edge D2D link's transmitter is located on the edge of an inner-region and the receiver lays in a designated range from it (we considered 100 m). Then, we shift the link on a straight line with a step of 50 meters towards the neighbouring competing BS to comment on the number of possibly interfering nodes if the link is associated to each one of the two BSs. As expected, when the link crosses the two-cell limit and is positioned almost in the middle of the distance between the two BSs, the number of the interferers is equal (in our case, this happened in a 150-meter shift). In such scenarios, it is the balancing objective that would guide the solution. The case is clearly similar for all deployed links due to their uniform distribution in space.

Finally, by applying the proposed weighted-sum method presented in the previous section, we investigate the problem in (18) in order to obtain an efficient trade-off of the objective functions. It has to be observed that these two objectives are not conflicting and therefore we are not considering optimal trade-off operating points on a Pareto frontier. The two objective functions were normalized according to the analysis detailed in subsection III-C. If we solve the weighted-sum method by applying the (18f) constraint as in [42], the obtained result, as shown in Fig. 8, indicates that there is linear non-conflicting relation of the two objectives. Therefore, as we can clearly observe, minimization of the second objective function can be interpreted as an increase to the max-min output of the balancing solution (i.e. first objective). For the results depicted in this figure, we applied a stepwise increase of the  $w_1$  weighting factor and a corresponding decrease to the  $w_2$  weight. In fact, it is the nominal practice to chose weights that their summation equals to one. Since the objectives are non-conflicting and their relative importance can be deemed as

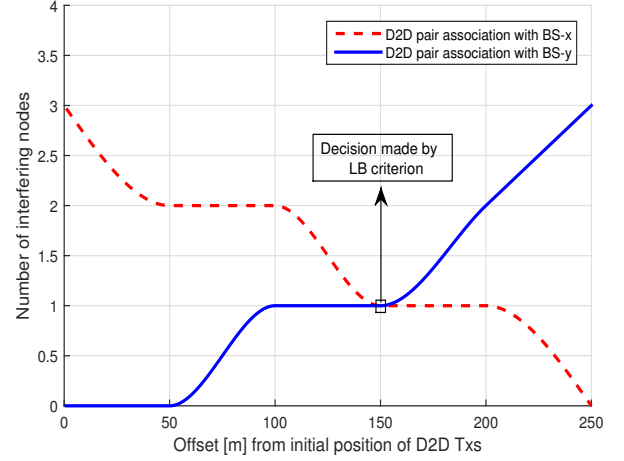


Fig. 7. Example of potential CUE interferers for a D2D link. The intersection point means equal interference probability for each possible association.

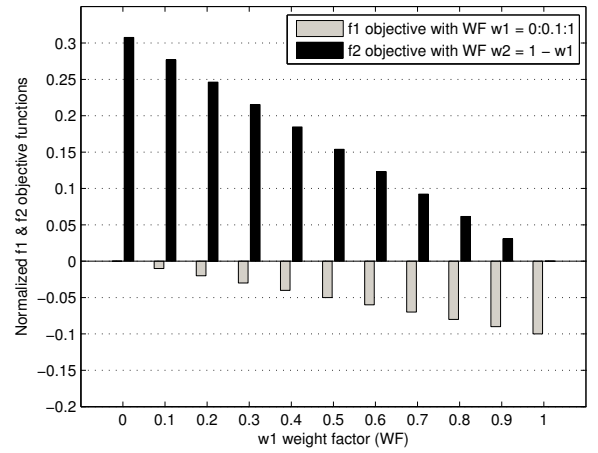


Fig. 8. Weighted sum method for MOCA-III bi-objective problem (sum constraint  $w_1 + w_2 = 1$  is being applied).

equal in general, the decision maker (in most of the cases could be operator-dependant) can set the aforementioned weights considering the relative magnitude of the objectives in order to achieve different network operating points.

#### D. Throughput performance

In our proposal, the solution of a CAS optimization problem will work as feed for the resource allocation technique described in IV. Among the proposed optimization formulations, we opt to use MOCA-I throughout the rest of the simulations as it provides the lowest running time complexity out of the three MOCA proposals. Indicatively, solving the three problems with the same CPU (INTEL(R) CORE(TM) i7-6500 @ 2.50 GHZ / 8 GB RAM), MOCA-I runs in 0.8 seconds, whereas MOCA-II and MOCA-III run in 1.4 and 2.3 seconds, respectively. By running this resource balancing-oriented setting, each D2D pair in the topology will be thereafter associated with a BS, aiming at contributing to the maximization of the minimum RB availability of the network.



Initially, we will compare the performance of the joint optimization problem presented in II-D with a set of different allocation techniques that use MOCA-I to decide over the cell association pattern for D2Ds. First, our *i*-RRA proposal that is detailed in subsection IV-A. Second, a differentiated FFR algorithm (for simplicity we abbreviate it as *d*FFR) [34], which uses the same FFR-based allocation rationale for D2D links but requires the cell outer-region DUEs to use the resources that cannot be used by the inner-region DUEs in order to guarantee the latter's welfare, providing thus a form of prioritization. Third is the soft FFR-based algorithm (*s*FFR) [35]. In that case, D2D and cellular UEs, being located in the same region (inner or outer), are able to utilize resources from the same available RB pool (e.g. in the center cell's inner region,  $F1$  is the available RB pool, whereas for outer region is  $F2$ ). This however can be potentially harmful for dense scenarios, because the existence of multiple D2D links will potentially lead to over-reuse of some of the limited resources (especially for cell-edge users) and, thus, performance might get degraded. Lastly, we apply a baseline random allocation algorithm, where D2D UEs can be assigned with a random RB from the whole frequency band that implies a rather unexpected performance. Fig. 9 shows the D2D sum-rate performance of all pre-mentioned resource allocation schemes which is upper bounded by the joint optimization problem's solution. As already discussed, the latter is solvable in the case of a small total number of D2D links that are randomly distributed in space because resource overlaps can be then avoided (no RB reuse by multiple DUEs). We use again the weighted sum method presented in III.C to run the optimization problem by assigning the weight factors  $w_1$  and  $w_2$  with 0.5. It is shown that the joint optimization solution outweighs the above algorithms by almost 17%, 63%, 132% and 104% on average in terms of sum-rate, respectively, **for the case of hexagonal grid scenario**. As expected, with the increase of the number of D2D links, the sum-rate improves proportionally in most of the depicted cases. However, in the last one (40 D2D links), only the joint optimization retains this increasing tendency by maximizing the total achievable throughput for DUEs, whereas in the rest of the algorithms, the developed interference due to the increasing number of users leads to a slight performance degradation. **Also, even though the achieved D2D sum-rate performance drops almost in half in PPP-Voronoi based deployments, the proposed method lays in between the joint optimal (but high complexity) method and the compared baseline techniques.**

For the rest of the performance evaluation, we investigate the resource allocation problem from a high D2D-related density point of view (150 D2D pairs, uniformly distributed).

Fig. 10 highlights the maximum sum-rate performance of the four resource allocation techniques for both cellular and direct transmissions. For this case study, we also compare the presented CAS methods (MOCA vs CbH) in order to visualize any effect on the throughput performance other than resource-aware utilization for the network. The difference per case is low, however if we consider the resource utilization savings already presented in this section, on top of 12% minimum RB availability, the *i*-RRA algorithm based on

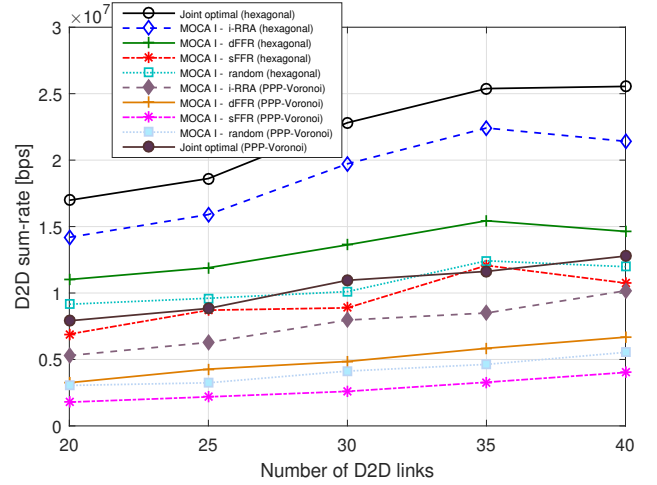


Fig. 9. D2D sum-rate comparison. In the joint optimal case a weight factor of 0.5 ( $w_1 = w_2 = 0.5$ ) is used for both objective functions in (6).

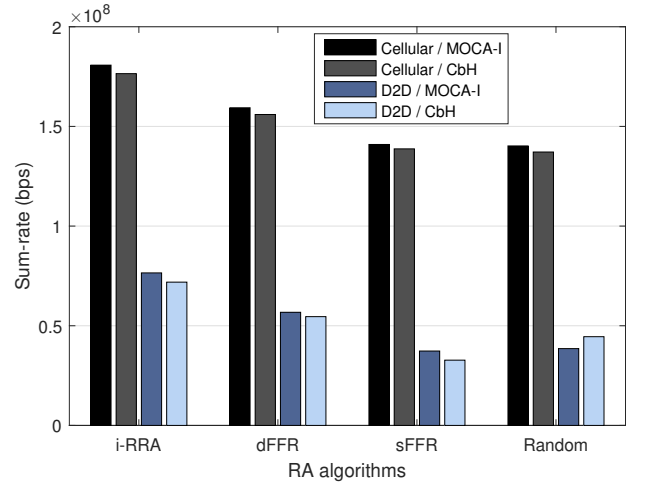


Fig. 10. Throughput performance for cellular and D2D connections in hexagonal based cellular networks.

MOCA-I CAS gives a slight improvement of almost 2.5% compared to the same algorithm with CbH. The aggregate throughput gain is more visible for D2D communications where 6.5% improvement is achieved through the MOCA-I / *i*-RRA two-stage implementation. By leveraging the MOCA-I CAS technique as the first step of the solution, the *i*-RRA for D2D communications outperforms the *d*FFR, *s*FFR and random RA techniques in a percentage of 35%, 105% and 98% respectively. In addition, the cellular performance follows the same trend, as the *i*-RRA algorithm is better than the rest of the methods for a percentage of 13%, 28% and 29%, respectively. **Complementary to it, Fig. 11 showcases the adaptability of the proposed methodology to more realistic deployments, represented by Voronoi cell tessellation. Again, a clear sum-rate performance improvement can be observed for both cellular and D2D users when leveraging the MOCA-I association method over the CbH one. Also, another representative fact is the further increased D2D sum-rate gain when using the *i*-RRA algorithm, while it outperforms the rest of the methods**

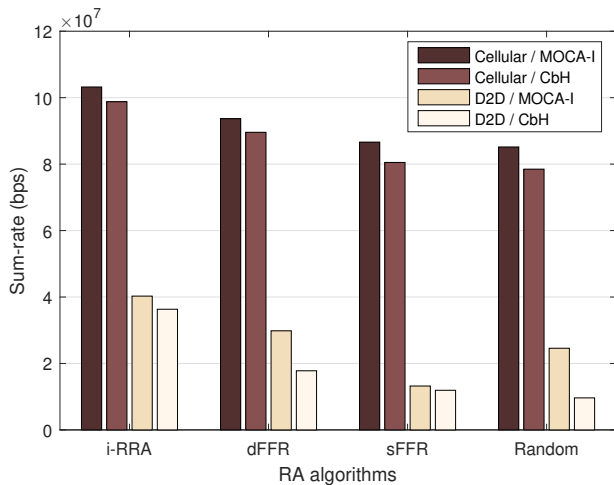


Fig. 11. Throughput performance for cellular and D2D connections in PPP-Voronoi deployments.

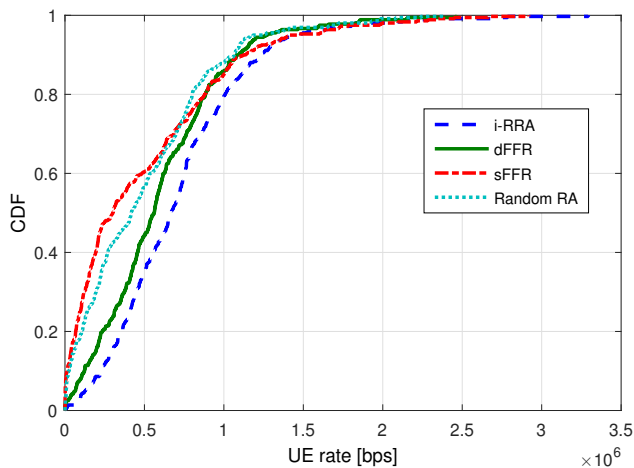


Fig. 12. UE rate CDF in hexagonal layouts based on MOCA-I.

in almost 36%, 204% and 65%, respectively.

Finally, Fig. 12 shows the CDF of the achievable rates for all cellular and D2D communications. Like before, MOCA-I is considered to be the decision mechanism used for the D2D-BS association. The i-RRR algorithm proves its supremacy and entails better throughput performance. In the 50<sup>th</sup> percentile, the i-RRR algorithm achieves a 17%, 110% and 48% better performance compared to dFFR, sFFR and Random methods, respectively. Considering the 90<sup>th</sup> percentiles, over 27% better rate performance of the i-RRR over the other RA techniques is shown. Again, same behavior is observed when investigating the UEs' throughput performance from the Voronoi tessellation point of view (Fig. 13), even though the average user throughput drops as compared to the hexagonal case.

## VI. CONCLUSIONS

In this paper, a two-stage approach for achieving spectrum efficiency and enhanced throughput for D2D enabled networks is proposed. First, a set of integer linear programming (ILP) optimization problems (namely MOCA) is devised, aiming to

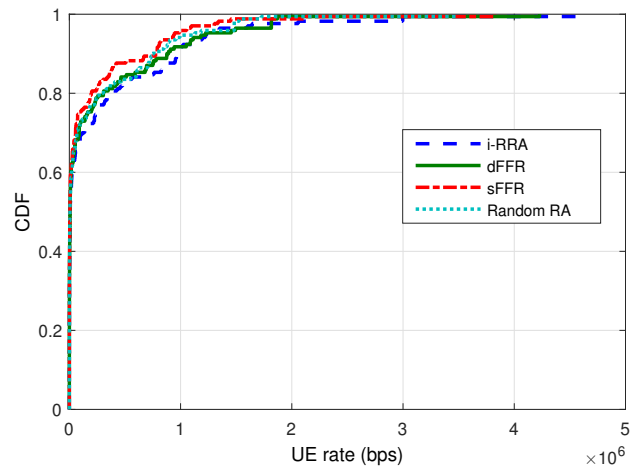


Fig. 13. UE rate CDF in PPP-Voronoi deployments based on MOCA-I.

optimize the cell association (CAS) aspect for D2D communications with respect to resource limitations, interference and network congestion episodes. The proposed set of optimization problems is amenable for a centralized implementation, something that could potentially be in-line with emerging cloudified RAN-based mobile networks. Then, based on the output of the cell association solution, a low-complexity iterative randomized algorithm for D2D communications that considers different RB pools for CUEs and DUEs is applied. The proposed framework is compared with baseline methods as well as related works in the literature. In terms of resource efficiency, the CAS optimization entails a balanced association of the distributed D2D UEs to the deployed BSs that can be interpreted as valuable resource savings and network capacity ease; over 12% of resource savings can be admitted by this method compared to a path-loss based heuristic one. Then, the proposed iterative randomized algorithm, called i-RRR, provides a fast and effective solution in terms of sum-rate performance when compared to other existing algorithms. Over 34% of D2D sum-rate improvement can be realized via i-RRR, with a non-degrading cellular achievable performance.

### A. Future Work

The proposed cell association framework could be potentially applied equally to dense small cell networks overlaying a macro-cell infrastructure. In that case, the problem of cell association for D2D users might have an increased complexity due to higher number of potential pairs between small cells and D2D links. This opens the path for innovative greedy, heuristic algorithms to be devised to allow for a real-time, scale-free operation. Also, a highly challenging area for resource management relates also to D2D with high mobility such as, for example, in vehicle-to-vehicle (V2V) communications operating on the licensed spectrum.

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